System Level Evaluation of Interference in Vehicular Mobile Broadband Networks

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Abstract — **This paper presents results from a novel OFDMA multi-cell mobile broadband system-level simulator. The tool is used to statistically characterize uplink and downlink inter-cell interference. Fully loaded interference studies cannot be performed on real-world networks until they have been fully deployed. As such, interference analysis and management must be accurately performed pre-deployment using detailed network simulators. This paper discusses our simulator architecture and the steps necessary to reduce computational complexity inherent in such simulations. The paper then demonstrates the impact of inter-cell interference in OFDMA networks. The results demonstrate that it is the frame-to-frame fluctuations in interference, and not the received signal level, that dominate inaccuracy in the Channel Quality Index (CQI). CQI errors lead to the wrong MCS mode being chosen by the AMC algorithm and this leads to throughput reduction. Results show that this problem is exacerbated by high vehicular speeds and the absence of interference randomization. Compared to ideal MCS selection, throughput reductions of up to 45% are reported.**

Keywords- mobile broadband; interference characterization; cellular; WiMAX; system level evaluation.

I. INTRODUCTION

This paper evaluates the inter-cell interference performance of a Wave-2 mobile WiMAX system. The simulator is based on the IEEE 802.16m amendment, which provides the basis for next generation mobile WiMAX systems. WiMAX uses scalable OFDMA in the radio access network [1]. In order to achieve the spectral efficiency and per-sector throughput required by voice, data and media applications, WiMAX utilizes Adaptive Modulation and Coding (AMC) and Multiple Input Multiple Output (MIMO) antenna processing. To achieve high user capacities it is necessary for the network to perform well at high traffic load. Billions of dollars have been invested in such networks [2] and unless deployed correctly, these can collapse under heavy load due to self-interference. The commercial success of mobile broadband networks is dependent on accurate interference characterization and management. It is therefore critical, pre-deployment, to accurately evaluate system level performance in the presence of uplink (UL) and downlink (DL) interference. It is also important to understand how interference is affected by the radio environment and a wide range of propagation scenarios. Due to real-world difficulties in loading a network and varying the propagation scenarios during drive tests, the comprehensive interference characterization of multi-cell systems cannot easily be achieved in practice. Heavy UL traffic loads are particularly difficult to engineer in controlled tests. This makes accurate interference characterization via simulation a vital step prior to network deployment.

Interference arises in the form of inter-cell and intra-cell interference. Whereas intra-cell interference is relatively easy to manage by means of orthogonal frequencies and scheduling strategies, inter-cell interference is problematic and remains a key issue in OFDMA based mobile cellular networks. This arises since in broadband wireless networks, sector frequencies are reused in adjacent cells to improve spectral efficiency. The problem is particularly acute at the cell boundaries, where wanted signal powers are weak and interfering signal powers are strong; resulting in reduced user throughput. Characterization of inter-cell interference for OFDMA networks is not well addressed in the literature – particularly on the UL. This is mainly due to the complexity of simulating a vast quantity of links over a statistically significant time period.

II. BACKGROUND

In order to characterize interference accurately in a mobile broadband network it is necessary to model a multi-cell environment that implements a realistic cellular reuse factor, uses full size frame structures over many frames, and implements subcarrier allocation and packet scheduling.

As discussed in [3], the link budget constraint on the UL of any mobile network necessitates the need for smaller cell sizes. The use of small site-to-site distances makes for highly interference limited systems. In order to analyze the UL interference, knowledge is required of the desired MS location, as well as the relative locations of all other interfering MSs. All the necessary fading channels must then be computed for the scheduled users in each frame. The authors in [4] considered interference randomization on both the UL and DL of a WiMAX system. However, they failed to implement a full system level simulator. The authors in [5] examined UL performance using a proprietary simulator (SHINE). This paper also explores a range of complexity reduction techniques. These are vital in order to create a simulator that can accurately characterize interference in a timely manner.

Complexity can be reduced by simplifying the computation of interference. In [6] the subcarriers from adjacent cells are simply scaled by a 'loading factor' to mimic the loading process, rather than accurately scheduling users and computing the resulting UL and DL interference. Although other simulators make use of correlated fast fading models, they commonly use random [7] or uniform [8] MS locations between drops, and uncorrelated (spatially) log normal shadowing [9].

To aid complexity reduction, many simulators use a much reduced frame size. In [8] the authors use just 48 sub-carriers and 6 sub-bands. Very few papers use the full number of subchannels and slots per frame. In [9] the full frame structure is implemented as per [10], however they do not consider power control, scheduling, or UL traffic.

Although many commercial network simulators exist, such as OpNet and QualNet, these tend to provide weak physical layer support. QualNet uses bit error rate (BER) look up tables that already include the fast-fading effects. Accurate simulators need to work with instantaneous performance in a fading channel, and not the expected performance averaged over the fading processes.

In this paper, a system-level simulation framework is presented that allows the performance of a Wave-2 mobile WiMAX system to be derived. The simulator closely follows the Evaluation Methodology Document (EMD) [10] in terms of its system parameters (such as transmit powers and antenna patterns) and simulation parameters (cell configuration, frame structure and traffic model). Enhancements above and beyond the EMD baseline are highlighted as they are introduced in the paper.

Our system implements AMC alongside Dynamic Transmit Power Control (DTPC) on the UL [11]. It schedules and models all users in both the reference and interfering sectors. Unlike other reported works, a fully temporally and spatially correlated model is used for fast fading and shadowing [12]. The simulator comprehensively models the mobility of users (indoor, outdoor pedestrian and vehicular) to allow the analysis of fast link adaptation. The bespoke spatial channel model includes a realistic range of K-factors, RMS delay spreads and angular spreads.

A PHY layer abstraction technique known as Received Bit Mutual Information (RBIR) is used to predict the instantaneous BLER. The abstraction model has been validated against link-level results from our own link-layer simulator. This in turn has been validated against results obtained from carrier-class mobile WiMAX equipment. Our novel AMC algorithm uses the ‘effective’ SINR (ESINR), as its Channel Quality Index, to calculate the optimal burst profile (i.e the MCS mode) for each user in order to maximize throughput for a given BER requirement. This ESINR is calculated from all the subcarriers allocated to that user using the RBIR technique. We then simulate the full frame structure including UL and DL. We implement the mandatory PUSC subcarrier permutation scheme together with a detailed packet scheduler. The scheduler runs using a proprietary proportional fair (PF) algorithm. It is applied to all the WiMAX traffic classes in strict priority to provide class prioritization. As per the EMD baseline our simulator:

- Models a tri-sector multi-cell environment with micro and macro scenarios,
- Models full size frame structures for UL/DL with PUSC,
- Uses correlated fast fading,
- Implements a range of MIMO modes,
- Uses an accurate and validated PHY abstraction model.

In addition our simulator:

- Exhaustively models all interferers,
- Uses a sophisticated correlated shadowing model with a validated autocorrelation function (ACF) and continuity of user mobility between frames,
- Implements AMC and AMS with channel feedback delay,
- Implements a proprietary PF scheduler with service class prioritization,
- Implements DTPC.

III. Simulator Description

A. System Overview

In this paper our results are confined to a SISO system. We also assume perfect channel estimation and synchronization. Equal power per subcarrier on the DL is applied. A full-buffer traffic model is assumed with best effort (BE) flows, since these most clearly highlight the impact of interference on AMC performance.

TABLE I. LINK AND SYSTEM SIMULATOR PARAMETERS

Parameters	**Value**
Carrier frequency	2.5GHz
Transmission bandwidth	5MHz
FFT size	512
Cellular configuration	Hexagonal cell/2 tiers/7 cells
Antenna patterns	3 sectors
Frame length	5ms (48 OFDMA symbols)
Data symbols	28 DL/9 UL
Subchannels	15 DL/17 UL
MCS modes	QPSK 1/2, 3/4, 16QAM 1/2 2/3, 64QAM 2/3, 3/4
AMC BER threhold	10^{-6}
MCS feedback delay	0 and 3 frames
Frequency reuse factor	1/3
Antenna scheme	SISO
Scheduling algorithm	Round robin, (1 subchannel/partition)
Mobility	Pedestrian (3kmph) and Vehicular (120kmph)
Penetration loss	10dB
Traffic class	Best Effort
Traffic model	Full buffer
Shadowing SD	8dB
De-correlation distance	50m
Power control, P_{nom}	21.4dB
Spatial channel model	CDL using spatial correlation
Pathloss model	COST 231 Hata

Tables I and II summarize the key system and simulation parameters. In mobile WiMAX the minimum resource unit is a ‘slot’. This is 1 subchannel x 2 OFDM symbols on the DL and 1 subchannel x 3 OFDM symbols on the UL. Each slot is dynamically assigned to an MS using the packet scheduler.

TABLE II. SYSTEM PARAMETERS

Parameters		Value
BS	Transmit power	43dBm
	Antenna height	32m
	Antenna gain (boresight)	17dBi
	3dB beamwidth	70°
	Front-to-back power ratio	20dB
	Number of antennas (Rx and Tx)	2
	Antenna spacing	4λ
	Noise figure	4dB
	Cable loss	2dB
MS	Transmit power	23dBm
	Antenna height	1.5m
	Antenna gain (boresight)	0dBi
	Antenna pattern	Omni
	Number of antennas (Rx and Tx)	2
	Antenna spacing	λ/2
	Noise figure	7dB
	Cable loss	0dB

B. Link-Layer Simulator Description

The link-level simulator is fully described in [13] and the results have been fully validated against carrier class equipment.

C. Spatial Channel Model (SCM)

A correlation-based Cluster Delay Line model is used with parameters taken from the 'Urban Macrocell' scenario (Table III). The full power delay profile is provided in [10].

TABLE III. CHANNEL MODEL PARAMETERS

Scenario	Cell Radius	(N)LOS	AS (BS,MS)
Urban Macrocell	500m	NLOS	2°, 15°

D. Pathloss, Antenna Gain and Shadowing

BS and MS heights of 32m and 1.5m respectively are used in the modified COST 231 Hata path loss model ('Urban Macro cell') shown in (1). The carrier frequency f [GHz] lies in the range $2 < f < 6$, as defined in [10].

$$PL[dB] = 35.2 + 35\log_{10}(d) + 26\log_{10}(f/2) \qquad (1)$$

In (1) d is defined in meters and represents the BS-MS separation distance. At the BS a Uniform Linear Array (ULA) is assumed with an antenna pattern as defined in [10]. The MS are assumed to have omni-directional antenna patterns. We implement a spatially correlated shadowing model as proposed in [12]. This is used to generate the shadowing values for the BS-MS links. The parameters are summarized in Table IV.

TABLE IV. SHADOWING PARAMETERS

Parameter	Value
Shadowing SD	8dB
Decorrelation distance	50m
Number of sinusoids [12]	500
Frequency resolution [12]	0.002
Spatial resolution [12]	0.5m
Waveform table size [12]	1000

E. Link-to-System Mapping (PHY Abstraction)

To simplify the interface between the link and system level simulations, whilst still modelling dynamic system behavior, a technique known as Effective SINR Mapping (ESM) can be used. This compresses the SINR (per subcarrier) vector into a single ESINR. In this work the Mutual Information ESM (MIESM) approach is applied. The technique is described fully in [14]. This approach has been exhaustively validated against our link-level simulator.

F. Simulator Complexity

Channel information for 107,520 links is required to compute a single time slot in the simulator. This is in addition to performing the permutation, link adaptation and scheduling algorithms. In order to reduce complexity the channel is assumed to remain stationary over a 'slot'. Only 512 subcarriers are used and the analysis is limited to the 7 central cells. It is shown in [15] that the second tier of interferers can be ignored. Statistics are only collected for the central cell. In order to further reduce computation time the channel responses are calculated offline.

IV. RESULTS

A. Signal and Interference Variability

In this paper we report results assuming 1) each active user is allocated a random subchannel in each time slot with PUSC, 2) each active user is scheduled the same subchannel across all time (horizontal strip) with PUSC, and 3) each active user is allocated a random subchannel in each time slot without any subcarrier permutation. The results were collected with all users at a) pedestrian speed (3kmph), and b) vehicular speed (120kmph).

Our novel fast link-adaptation operates by collecting the CQI per MS in the form of the ESINR over all subcarriers allocated to that MS in a reference frame. The algorithm then uses this information to predict the highest order MCS mode that can be supported by each MS whilst maintaining a BER that can be specified for each service flow as part of the QoS parameters. Here, for simplicity, all users have a BER target of 10^{-6}. The simulator was run with: a) a zero frame delay (i.e. perfect per-frame CQI knowledge), and b) a 3 frame feedback delay (as per the EMD). Due to the fact that ESINR values have different bounds in different MCS modes, which distorts representation of the data, the SIR, SNR and SINR values are shown over all of a user's allocated subcarriers in a frame as a mean value. These are now denoted by ASIR, ASNR and ASINR respectively.

TABLE V. DL SUB-FRAME CQI ERROR RESULTS

Speed	Allocation	ASIR Err Var (dB)	ASNR Err Var (dB)	ASINR Err Var (dB)
Ped	Random (PUSC)	26.8	3.3	15.5
	H. Strip (PUSC)	26.6	3.4	15.6
	Random (No Perm)	33.0	8.9	20.7
Veh	Random (PUSC)	57.1	5.8	37.8
	H Strip (PUSC)	56.6	5.9	39.2
	Random (No Perm)	64.4	11.8	44.9

Tables V and VI show the variance of errors between the CQI in the frame that the AMC uses as reference (with 3 frame delay), and the current frame, for all active users over 1000 frames. Table V shows the DL case, and table VI shows the UL case.

TABLE VI. UL SUB-FRAME CQI ERROR RESULTS

Speed	Allocation	ASIR Err Var (dB)	ASNR Err Var (dB)	ASINR Err Var (dB)
Ped	Random (PUSC)	17.8	3.3	6.1
	H. Strip (PUSC)	10.5	3.4	4.9
	Random (No Perm)	27.8	9.7	13.5
Veh	Random (PUSC)	27.1	6.3	9.5
	H. Strip (PUSC)	25.3	6.5	11.0
	Random (No Perm)	47.4	14.1	20.3

Table V shows that in the pedestrian case, the ASNR error variance is not affected by the allocation strategy as long as PUSC is enabled. If there is no subcarrier permutation, however, the value more than doubles due to the removal of the frequency diversity provided by PUSC. At vehicular speeds exactly the same trend is displayed but with higher values. This is because the channel will have changed more significantly over the 3 frames in the vehicular case. The ASIR values follow the same trend as the ASNR values in all cases, but are significantly higher; nearly ten times higher in the vehicular case with random subchannel allocation and PUSC.

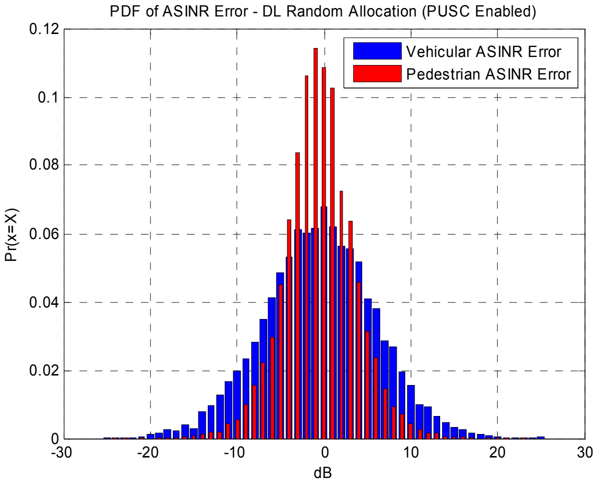

Figure 1. ASINR error in vehicular and pedestrian scenario

Mode selection is based on the ESINR from the delayed frame so as these ASINR errors equate to ESINR errors, they will produce MCS mode choice errors. If the ESINR in the scheduled frame is better than that predicted by the AMC algorithm, using delayed CQI information, then the scheduler MCS mode will be too low and network capacity will be reduced. If the opposite is true, then the scheduled MCS mode will be too high and this leads to high BLER. It is clear that in this scenario the ASINR error is completely dominated by the ASIR term. This means that it is the fluctuation in interference power and not that in the signal power that controls the accuracy of the AMC algorithm. This highlights the necessity for interference characterization and mitigation. The fact that the ASINR error variance is significantly higher in the vehicular case means that worse system throughput will be experienced and it highlights the difficulties related to accurate channel feedback in vehicular communications systems. The difference between the ASINR error in the vehicular and pedestrian cases is shown in Figure 1 for random allocation with PUSC enabled.

In the UL case the same trends and very similar values can be seen for the ASNR error variance values. It can be seen, however, that the ASIR error variance values are significantly lower than the DL case and this leads to lower ASINR error variance. The reduced error variance observed in the UL case is due to the use of lower UL transmit powers, which results in a smaller dynamic range in the received interference power. The fact that the ASINR is significantly worse without permutation in both the UL and DL case highlights the need for frequency randomization or frequency coordination techniques [3].

Results from Table VI show that the use of a horizontal strip schedule reduces the ASINR error variance in the UL pedestrian case. This is due to the fact that unlike the random allocation scheme, the interference now comes from a constant source. This reduction is not seen in the DL case because the BS transmits with equal power on all subcarriers irrespective of the allocation strategy. A much smaller reduction in the ASIR variance is observed in the vehicular case as the relative motion of the MSs is much greater, causing larger fluctuation in the SIR over the 3 frame period.

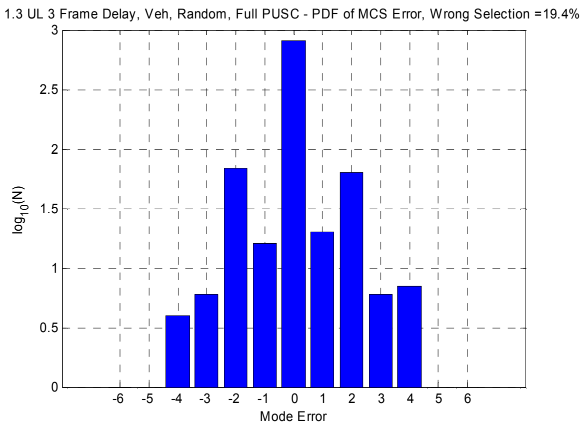

Figure 2. UL MCS mode choice error for MS 1.3 at vehicular speed

B. *Effect of Signal Variability on Throughput*

As discussed in the previous section, the ASINR errors lead to MCS mode choice errors, which in turn lead to capacity reduction. Figure 2 shows the MCS mode choice errors for the worst-case UL user (MS 1.3, i.e. user 3 in sector 1) in the vehicular case, with random subchannel allocation and PUSC. In this case the wrong MCS mode is chosen 19.4% of the time and this leads to a throughput reduction over the 1000 frames (compared with perfect per-frame CQI knowledge) of 35% from 114kbps to 74kbps. If no subcarrier permutation is applied, the wrong MCS mode is chosen 39.3% of the time, and mode selection errors all the way up to ±6 are seen. In this case the throughput falls even further to 58kbps.

On average, over all of the users, it was found that on the DL the MCS mode choice error for the pedestrian case was 20% with PUSC and 23% without PUSC. These values rise to 40% and 45% in the vehicular case. MS 1.3 is the worst case DL user suffering a 31% reduction in throughput due to inaccurate CQI in the vehicular case (535kbps reduced to 368kbps). Without subcarrier permutation this falls to 307kbps (a 43% reduction).

C. *Autocorrelation of Channel Quality Information*

The use of autoregressive filters to implement AMC algorithms that use channel prediction has received much interest in the literature (see [16] and references therein). Figure 3 shows the autocorrelation function of the ASINR error between the delayed frame and the current frame when using a horizontal strip schedule for MS 0.3. It can be seen that, in the pedestrian case, the autocorrelation follows a smooth function and does not fall to zero until there is a 4 frame shift. In the vehicular case the correlation falls quickly to values below 0.1 with a 2 frame shift, and to zero after a 3 frame shift. This shows that unlike in the pedestrian case, at vehicular speeds the channel changes too rapidly over a 3 frame period to allow the effective implementation of an autoregressive filter.

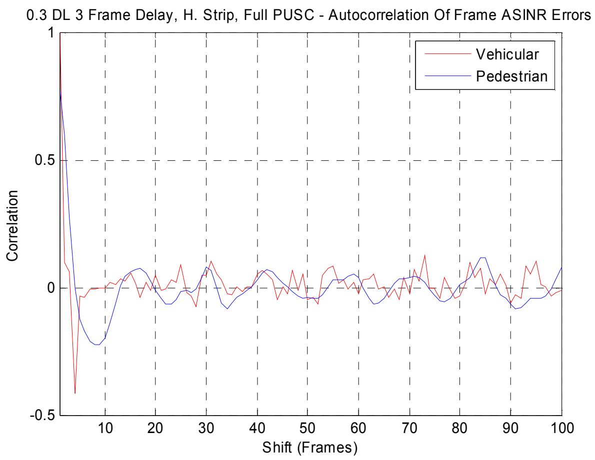

Figure 3. Autocorrelation of ESINR errors

V. CONCLUSIONS

This paper has introduced a detailed and efficient OFDMA based system level simulator. This simulator enables the investigation of complex issues such as inter-cell interference and MCS mode selection on both the UL and DL, with a variety of traffic speeds and subcarrier allocation strategies.

It was shown that it is the fluctuation in interference power, and not in signal power, that dominates the inaccuracies seen in the predicted CQI. This prediction is used by the fast AMC algorithm to select the MCS mode in future frames. Selection of incorrect MCS modes causes a reduction in throughput. In the worst case scenario, at vehicular speeds, the inaccurate CQI information caused a 31% reduction in DL throughput and a 24% reduction in UL throughput. Without the use of subcarrier permutation the throughputs fall even further. It was found that the CQI error was smaller on the UL due to a reduced ASIR error variance, and could be reduced further (i.e. improving system performance) on the UL using a horizontal strip schedule.

Our results highlight the necessity for detailed interference characterization and management in OFDMA based networks. Although the simulator is based on mobile WiMAX, its algorithms, methods and results can easily be extended to other mobile broadband wireless networks, such as LTE.

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VI. REFERENCES

[1] "IEEE Std 802.16e-2005 and IEEE Std 802.16-2004/Cor 1-2005," 2006.

[2] “Sprint Nextel Announces 4G Wireless Broadband Initiative with Intel, Motorola and Samsung,” http://www2.sprint.com/mr/news dtl.do?id=12960.

[3] G. Boudreau, J. Panicker, N. Guo, R. Chang, N. Wang, and S. Vrzic, "Interference coordination and cancellation for 4G networks - [LTE part II: 3GPP release 8]," *IEEE Communications Magazine*, vol. 47, pp. 74-81, 2009.

[4] A. V. Sarad and S. Srikanth, "Improved interference diversity in multicellular OFDMA systems," *COMSNETS,* pp. 1-8, Jan. 2009.

[5] M. Hunukumbure, B. Upase, and S. Vadgama, "Modelling interference margins in FFR enabled WiMAX systems for cell dimensioning," *IEEE PIMRC*, pp. 1-5, Sept, 2008.

[6] B. J. Lee, J. W. Kim, J. C. Kim, and C. G. Kang, "System-level Performance of MIMO-based Mobile WiMAX System," *IEEE MWS*, pp. 189-194, July 2009.

[7] M. Shariat, A. Ul Quddus, and R. Tafazolli, "On the efficiency of interference coordination schemes in emerging cellular wireless networks," *IEEE PIMRC*, pp. 1-5, Sept 2008.

[8] A. L. Stolyar and H. Viswanathan, "Self-Organizing Dynamic Fractional Frequency Reuse for Best-Effort Traffic through Distributed Inter-Cell Coordination," *IEEE INFOCOM*, pp. 1287-1295, April 2009.

[9] S. Hamouda, C. Yeh, J. Kim, S. Wooram, and D. S. Kwon, "Dynamic hard Fractional Frequency Reuse for mobile WiMAX,". *IEEE PerCom*, pp. 1-6, March 2009.

[10] J. Zhuang, L. Jalloul, R. Novak, and J. Park, "IEEE 802.16m Evaluation Methodology Document," 2009.

[11] Y. Q. Bian, A. R. Nix, E. K. Tameh, and J. P. McGeehan, "MIMO-OFDM WLAN Architectures, Area Coverage, and Link Adaptation for Urban Hotspots," *IEEE Transactions on Vehicular Technology*, vol. 57, No. 4, pp. 2364-2374, 2008.

[12] Z. Wang, E. K. Tameh, and A. R. Nix, "Joint Shadowing Process in Urban Peer-to-Peer Radio Channels," *IEEE Transactions on Vehicular Technology*, vol. 57, No. 1, pp. 52-64, 2008.

[13] M. Tran, D. Halls, A. Nix, A. Doufexi, and M. Beach, "Mobile WiMAX: MIMO Performance Analysis from a Quality of Service (QoS) Viewpoint," *IEEE WCNC,* pp. 1-6, April 2009.

[14] L. Wan, S. Tsai, and M. Almgren, "A fading-insensitive performance metric for a unified link quality model," *IEEE WCNC,* pp. 2210-2114, April 2006.

[15] M. K. Karray, "Electromagnetic Exposure and Quality of Service in the Downlink of Wireless Cellular Networks," *ICWMC*, Sept. 2010.

[16] D. Rhee, J.H. Kwon, H. K. Hwang, and K. S. Kim, "Adaptive Modulation and Coding on Multipath Rayleigh Fading Channels Based on Channel Prediction," *ICACT,* pp. 5-10, Feb 2006.